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cooling systems. However, these calculations including passive methods for maintaining required room air temperature levels must be conducted according to regulations methodology. Therefore, the question arises, in which extent the results are varied for the overheating calculations. In addition, the impact of simulating with different time-step options or the leap year could be assessed. Furthermore, in default simulations daylight saving time is used. Hence, simulating only with summertime or correct schedule including both daylight saving time and summertime should be analysed. Additionally, investigating effect on simulations containing demand-based controlled systems, such as variable air flow ventilation system or occupant or natural lighting-based lighting system, the results variations with the same building models could be assumed.

Conclusion

The aim of this paper is to assess the impact of the undetermined building energy related simulation parameters presented in this study, such as first day of simulation, startup pre-simulation length and simulation splitting to sub-simulations. Five office modern buildings and five office parts of the building, situated in Estonia, were analysed.

The first parameter, consisting of the start of the simulation weekday comparison, showed the highest impact to the results. Depending on the weekday chosen, the net ventilation heating energy may vary up to 1.18 kWh/(m²×a) with the mean value of 0.43 kWh/(m²×a) or the net ventilation cooling energy can vary up to 0.95 kWh/(m²×a) (0.37 kWh/(m²×a) on the average). The delivered heating energy may vary up to 1.19 kWh/(m²×a) (mean value 0.45 kWh/(m²×a)) and the *EPV* up to 1.04 kWh/(m²×a) (mean value 0.45 kWh/(m²×a)). Room cooling and electricity consumption as well as definition of startup pre-simulation or simulation splitting is less sensitive to the overall results. In Estonia, the gap between different *EPV* criteria is 30 kWh/(m²×a) for office buildings. Therefore, up to 1.5% of reaching the desired upper *EPV* criteria is based on pre-simulation definition or dividing simulation into smaller sub-simulations. The gap can be over 3% of the desired result depending on the weekday to be chosen for the startup of the simulation. To avoid uncertainty at given extent for the day at the start of the simulation, a fixed weekday for the start of the whole-year simulation could help.

In conclusion, by the means of the analysed 5-day usage-based office buildings undetermined simulation parameters, we found:

- weekday of the first day of simulation to be considered as an additional variable regarding building energy or energy efficiency calculations;
- startup pre-simulation length and simulation splitting to be less sensible parameters compared to first day of simulation impact.

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Nomenclature

HVAC	heating, ventilation and air conditioning
MEP	mechanical, electrical and plumbing system
nZEB	nearly zero energy building
A	net heated floor area m²
A_{env}	envelope area of the building m²
EPV	energy performance value kWh/(m²×a)
H	specific heat loss W/K
SF	solar factor
SFP	specific fan power kW/(m³/s)
U	thermal transmittance W/(m²×K)
V	volume of the building m³
WFR	window-to-floor ratio
WWR	window-to-wall ratio

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The right way to do building simulations? Using Monte Carlo simulations, sensitivity analysis, and metamodeling on a design case

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Abstract

Monte Carlo simulations, sensitivity analysis and metamodeling are becoming popular in academia but are rarely applied in real building projects. In this case study, we demonstrate how a combined framework of these methods can aid decision-making in relation to building performance of nine 16-story residential buildings. We describe the processes before, during, and after a meeting between building engineers and the building owner. For preparation, BeDesigner was used to create, run, and analyse 5.000 Be18 simulations in roughly 4 hours. The meeting is initiated with a presentation of sensitivity analysis results to focus the attention towards the most influential design inputs. The 5.000 simulations are visualized with parallel coordinates plots in DataExplorer, which enable decision-makers to observe the consequences of different design choices and regulatory requirements. Real-time sensitivity analysis, TOR, highlights the parameters affected the most by the applied constraints, while histograms indicate favourable or disadvantageous design choices. However, no solutions exist among the 5.000 simulations, which is due to the vastness of the multi-dimensional input space and the decision-makers' numerous requirements. Using metamodels, 500.000 additional input combinations are calculated and from this extensive dataset a variety of solutions are found. It becomes clear that a "no-renewables" ambition necessitates costly counter-measures and makes it difficult to realize the architectural and indoor climate requirements. In conclusion, the combined framework improves the information quality for decision-making and significantly increase the likelihood of finding diverse, high-performing solutions within the same time-frame as traditional practice.

Introduction

Building regulations are gradually being tightened and the number of performance objectives steadily increase. In Denmark, the building energy frame has been reduced by 25% in 2006, 2010 and 2015 while constraints for thermal comfort and daylight have been added or strengthened (Danish Energy Agency, 2020). In 2023, regulations are expected to involve life-cycle-analysis and life-cycle-costs (Ingeniøren, 2020). At the same time, voluntary holistic assessment schemas, such as DGNB, are becoming increasingly popular (Danish Green Building Council, 2020). These circumstances make it harder to find code-compliant solutions and, at the same time, meet the ambitions of different stakeholders, e.g. from the building owner and the architects. In the iterative, interdisciplinary design process, the design team often address many design parameters in search of a solution to all requirements. In this process, building performance simulations (BPS) are used to assess many quantitative requirements while other constraints are evaluated using budget spreadsheets, expert judgement, or past experience. Since such assessments are performed by multiple actors at different companies, most important design decisions are made during interdisciplinary meetings. As building engineer responsible for BPS and code compliance, it is therefore a great challenge to find high-performing solutions and use the information gained from BPS to assist multi-actor decision-making.

First, we outline the typical approach to building simulations in Danish consultancy industry before shifting our attention to trends in academia and software developments. The common approach is to perform a manual parameter study in which a few selected design parameters are varied one-at-a-time based on prior experience and best estimates. The starting point is a reference model constructed on basis of the latest BIM-model combined with initial estimates for construction quality and HVAC system properties. For the parameter study, it is common to manually vary between five to ten design parameters one-at-a-time. The number of parameters and their variations increase when the requirements are difficult to meet. The resulting solutions, and potential design alternatives, are often presented in reports or in slideshows during design meetings. It often requires some compromises to choose a specific option. Sometimes, none of the presented solutions satisfy all stakeholders, e.g. if too costly or aesthetically undesirable, and more alternatives are requested, which require a new parameter study and subsequent meeting. A final note is that the one-at-a-time parameter study only covers a small part of the design space and is most likely to reveal sub-optimal solutions, which depend heavily on a good starting point (Østergård, Jensen and Mikkelsen, 2019).

The traditional one-at-a-time approach is contrasted by statistical methods such as Monte Carlo simulations and multi-objective optimization, which have become increasingly popular in academia (Tian *et al.*, 2018) (Kheiri, 2018). They make it possible to address a large number of design parameters and explore hundreds or thousands of design combinations. Multi-objective optimizations rely on algorithms to search for high-performing solutions under given constraints. Optimization are mostly done with respect to building control but research also address optimization of building design (Machairas, Tsan-grassoulis and Axarli, 2014). The optimisation usually results in a Pareto front of solutions from which anyone may be selected by making a trade-off between equally important objectives, e.g. energy demand and cost (Longo, Montana and Riva Sanseverino, 2019). However, these solutions may be unfavourable or sub-optimal if not all objectives, for example qualitative ones, have been considered or if the constraints have changed. Another consideration is that optimization try to avoid "poor" designs but such simulations may still contain valuable information, e.g. they can help persuade a stakeholder that a specific design approach yields unsatisfying performance.

The Monte Carlo method, on the other hand, rely on *random* sampling of input combinations, which facilitates sensitivity analysis, Monte Carlo filtering, and the construction of fast metamodels. Sensitivity analysis provide insight into model behaviour and parameter importance, which can help a design team to focus on the most influential inputs and disregard the insignificant ones (Pang *et al.*, 2020). This knowledge can be combined with Monte Carlo filtering, which reveals the consequences of any constraints applied to the simulation inputs or outputs (Østergård, Jensen and Maagaard, 2017a). Lastly, the metamodeling ability means that fast, simplified models of the current building simulation model can be constructed from the Monte Carlo simulations. Valid within the initial input space, metamodels allow for immediate computation of any design configuration and assess specific design changes. With Monte Carlo sampling, no constraints are given on beforehand, which "provides the maximum possible information for use in decision-making" and the search of solution is more flexible than optimization approaches (Wright, Nikolaidou and Hopfe, 2016)(Lee, Pourmousa-vian and Hensen, 2016). In addition, a comparison of structured one-at-a-time optimizations with random Monte Carlo simulations has shown that the latter provides better performing and more diverse solutions – even with the same number of simulations (~30) (Østergård, Jensen and Mikkelsen, 2019).

Initially, the ability to perform automated optimization and Monte Carlo simulations were facilitated by third party "add-ons" or customized scripting, e.g. BEopt, jEPlus, GenOpt, and Matlab. However, in recent years, several developers of BPS software have integrated the capability to define uncertainties and propagate these using random Monte Carlo sampling, e.g. DesignBuilder v. 6 (~2009) and IDA-ICE 4.8 (beta, ~2019). At the same time, it has become less of a burden to compute hundreds or thousands of building simulations due to advances of parallel computing and cloud computing. These developments have made Monte Carlo methods more accessible and easier to use, which may significantly increase their popularity in both academia and industry.

At least in the Nordic countries, the Monte Carlo methods, sensitivity analysis, and metamodeling are still highly uncommon in industry despite the great potentials shown in academia and the recent advances in software applications. This may be due to a number of reasons. First, it necessitates a different workflow for setup, computation, and communication. Stakeholders must also accept another "way-of-thinking". Instead of evaluating few deterministic simulations, design parameters are described by ranges or probabilities and the performance objectives are expressed by distributions. Another possible obstacle could be reluctance by project leaders, or building owners, concerned of increased cost and time for the computation of large numbers of simulations. A final reason may be lack of education or knowledge of these frameworks.

With this paper, we hope to break down the aforementioned barriers. We will demonstrate how to apply a combined framework denoted "MIBS" (Multivariate and Interactive Building Simulations), which rely on Monte Carlo simulations, sensitivity analysis, interactive visualizations, and metamodeling. For this real building case study, the work load and timeframe are comparable to traditional practice, i.e. the efforts needed to perform simulations, analyse results, and communicate the information as part of a multi-actor design process. Throughout the paper, we explain how the MIBS framework differs from typical practice and discuss advantages and disadvantages.

Methods

The case study involves three parts: 1) a meeting preparation phase in which design variations are assessed using building performance simulations and analysed by architectural engineers, 2) a design meeting where multiple decision-makers discuss design alternatives, and 3) subsequent updates of the design. In this section, we describe the building project denoted "Parkbyen", the building requirements, the stakeholder ambitions, the decision-making context, and the software used. We remark that the design process is considered from the perspective of the architectural engineer responsible for building performance simulations and compliance with building code. The building design case is provided by the engineering consultancy company MOE and comparisons of time-frames and workflows in common practice are based on MOEs experience, which are assumed representative for Danish consultancy practice. We remark that the MIBS framework has been applied to more than 10 projects in MOE so this is not an exclusive case.

Building description

The MIBS framework was first introduced to the project late in the conceptual design phase and close to the project delivery for municipal approval. At this point, the project consisted of nine identical, but differently rotated, high-rise buildings – each of 5.622 m² floor area. The façade design and floor plans were relatively fixed, see Figure 1 and 2. In contrast, the constructions and systems were still at a low information level with large variabilities.

Some important characteristics are as follows:

- Heated by district heating
- High heat capacity mainly due to exposed concrete slabs, 129 Wh/K m²
- 62 decentralized air handling units with supply and exhaust ducts leading to the façade in each apartment
- Minimum mechanical ventilation rates, ~0.3 l/s m²
- No mechanical cooling
- 62 decentralized water tanks
- Indoor temperature set point is 20°C (building code)
- Person load is 1.5 W/m² (building code)
- Equipment load is 3.5 W/m² (building code)

Based on experience, we have chosen 16 important design parameters to be varied with the Monte Carlo method, while keeping (supposedly) insignificant inputs fixed, such as pump and hot-water tank properties. The 16 design parameters and their variations are shown on Figure 3. Uniform (discrete or continuous) distributions are used for a several reasons: a) they must describe an unbiased design "variability" where all values are equally possible, b) it makes easier to observe trends when adding constraints, and c) they provide good coverage of the input domain for metamodeling. The variable inputs span an enormous 16-dimensional design space. We "explore" this design space with 5.000 random Monte Carlo simulations, which is considered sufficient to construct accurate metamodels for a more complete coverage of the multidimensional space. The software applications described below have been used to enable this setup.

Performance requirements

At the time the MIBS framework was introduced to the project, the main focus was to balance the design parameters to meet the normative whole-building energy demand without exceeding the budgets. The energy frame for primary energy demand was 30.2 kWh/m² according to Danish building regulations BR18. In terms of thermal comfort, BR18 requires that the temperature in the most critical room must not exceed 27°C for more than 100 hours a year. Daylight requirement is met when the "corrected" glass-to-floor-ratio is at least 10% for each room. The ratio is corrected for shadings, light transmittance, etc. Only a few, "critical" rooms are assessed in terms of thermal comfort and daylight availability at this design stage, see Figure 2. To sum up, the design team had to address three regulatory, quantitative objectives; primary energy demand, thermal comfort risk, and glass-to-floor-ratio which are often conflicting. E.g., increasing the glazing area may induce overheating or increase energy demand.

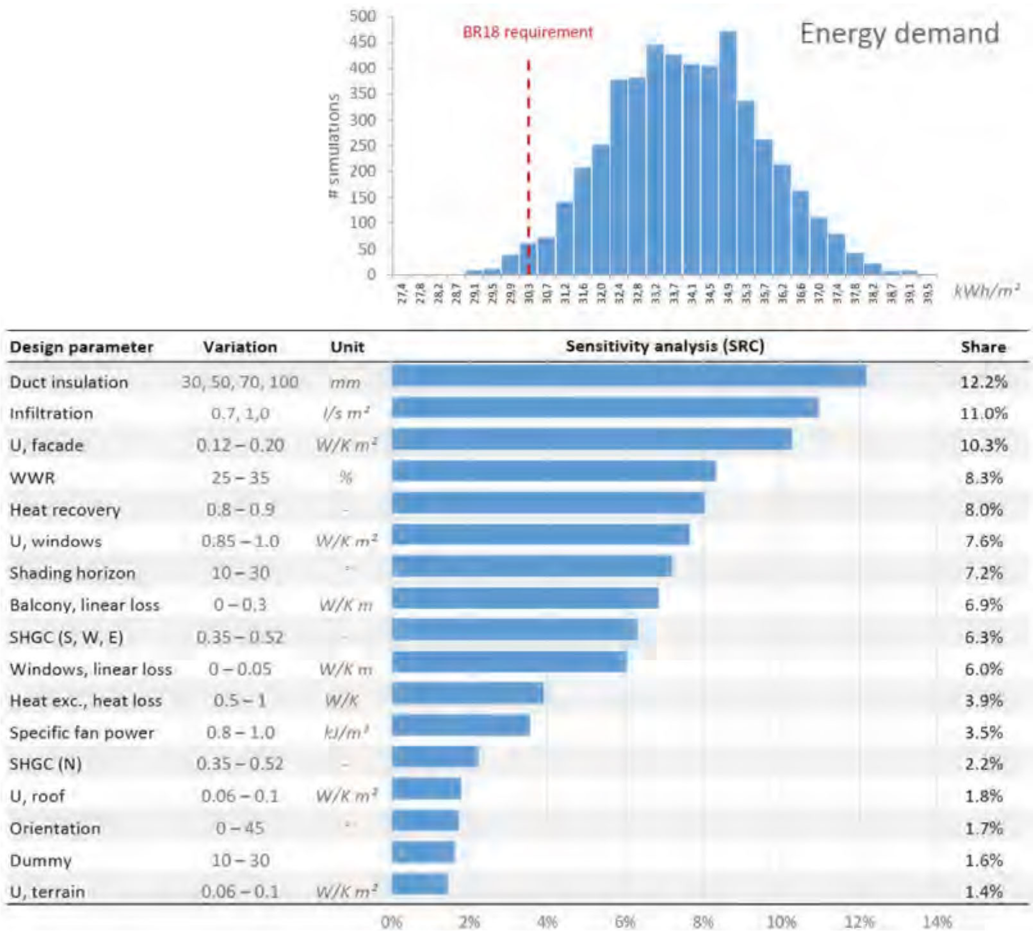
Figure 1 Illustration of façade concept and building rotations. Illustration: TRANSFORM.

Figure 2 Floor plan with indication of rooms selected for thermal comfort evaluation (green, blue) and daylight availability (blue, yellow). Illustration: TRANSFORM.

In addition to the regulatory requirements, the building owner requests a solution with no solar cells. To understand the importance of this request, it is worth to notice that due to the frequently strengthened requirements in the building code most new buildings include solar cells. This statement can be supported by the development in medium-sized and large residential building projects in MOE. There, 18 of 27 (67%) projects included solar cells with the BR10 regulations having an energy frame of ~53 kWh/m², which applied from 2010 to 2015. In comparison 16 of 17 (94%) projects included solar cells for BR15 and BR18 project.

Software – BeDesigner and DataExplorer

In Denmark, the normative whole-building energy demand is assessed using the Be18 software, which is based on EN 13790. Be18 includes a module for



Design parameter	Variation	Unit	Sensitivity analysis (SRC)	Share
Duct insulation	30, 50, 70, 100	mm		12.2%
Infiltration	0.7, 1,0	l/s m²		11.0%
U, facade	0.12 – 0.20	W/K m²		10.3%
WWR	25 – 35	%		8.3%
Heat recovery	0.8 – 0.9	-		8.0%
U, windows	0.85 – 1.0	W/K m²		7.6%
Shading horizon	10 – 30	°		7.2%
Balcony, linear loss	0 – 0.3	W/K m		6.9%
SHGC (S, W, E)	0.35 – 0.52	-		6.3%
Windows, linear loss	0 – 0.05	W/K m		6.0%
Heat exc., heat loss	0.5 – 1	W/K		3.9%
Specific fan power	0.8 – 1.0	kJ/m³		3.5%
SHGC (N)	0.35 – 0.52	-		2.2%
U, roof	0.06 – 0.1	W/K m²		1.8%
Orientation	0 – 45	°		1.7%
Dummy	10 – 30			1.6%
U, terrain	0.06 – 0.1	W/K m²		1.4%

Figure 3 Screenshot from BeDesigner with input variations, distribution of calculated energy demand, and sensitivity analysis (based on standardized regression coefficients).

evaluation of thermal comfort in a "critical" room for residential buildings. Simulation inputs and results are stored in XML files. Based on a reference Be18 model, the novel tool, BeDesigner, is used to define variable inputs and run Monte Carlo simulations with Be18 as "engine" (MOE|BuildingDesign, 2019a). With an Excel interface, the user can quickly select inputs from the reference model and assign probability density functions to represent their uncertainty or variability. Next, a large number of input combinations are constructed from random sampling. After parallel simulations, sensitivity analysis is automatically performed for each output using linear regression (standardised regression coefficients). This shows how much each variable input contribute to the output variation. Thus, sensitivity analysis indicates the parameters relative importance and helps identify which inputs require the most attention and which can be ignored for the time being. The final step in BeDesigner is to create a text-file containing Monte Carlo input and outputs values for further analysis in DataExplorer.

DataExplorer is an online tool for visualization and analysis of multivariate data (MOE|BuildingDesign, 2019b). The simulation data is displayed in an interactive parallel coordinates' plot (PCP), where each simulation is represented by a line showing its input and output values (see Figure 4). The user, or in this case multiple decision-makers, can search for solutions and test different design strategies by applying constraints to the coordinates.

For each coordinate, a histogram shows the parameter's distribution with the current set of constraints. Initially, the bins are equally wide since we have described input variability using (discrete or continuous) uniform distributions (see top PCP). When adding constraints, some input distributions become skewed. The widest bins therefore indicate favourable input ranges since most of the remaining simulations intersect in those. Thus, the histograms help reveal both favourable and disadvantageous input values for the applied constraints range (see bottom PCP). Real-time sensitivity analysis guides the users to those parameters, which have been affected the most by a given set of constraints (Østergård, Jensen and Maagaard, 2017b). This makes it easier to observe the consequences of specific design strategies or criteria.

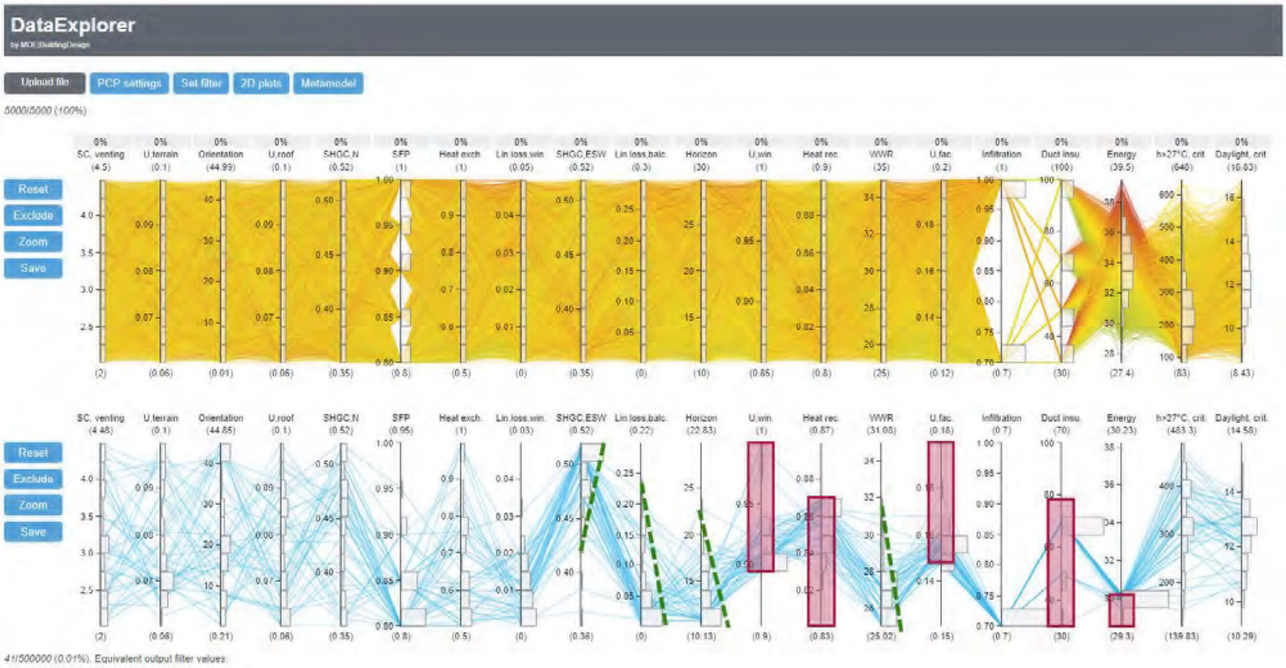


Figure 4 Parallel coordinates plots with 5.000 Be18 simulations (top) and 500.000 metamodel calculations (bottom). Filters are highlighted with red boxes and examples of histogram trends are exaggerated with green, dashed lines.

Finally, DataExplorer enables fast metamodeling using artificial neural networks.[1] Additional design evaluations are often necessary when adding multiple constraints to a large multidimensional dataset. For this case study, the 5.000 randomly selected points cover only a very sparse part of the 16-dimensional design space. But metamodels, “trained” from the 5.000 simulations can calculate 100.000’s additional design combinations, in the original space or in a subspace, which allow for a more thorough investigation in a secondary parallel coordinate plot.

The metamodeling feature also address a shortcoming of the PCP visualization that cannot show the expected outcome of changing a single variable by specific amount. To elaborate, the metamodels enable the design team to assess how much an input change, made anywhere in the multidimensional design space, will affect each output on average (and their minimum and maximum output changes), see Figure 5. E.g. the effect of an incremental increase in SHGC (solar heat gain coefficient) of 0.1 will depend on other design parameters, such as WWR (window-wall-ratio), shading, etc., and therefore the effect on energy demand could be 1 kWh/m² on average, but with smaller values when WWR is low and shading high, and vice versa.

Results and discussion

Preparation for design meeting

Based on experience and knowledge of building physics, a total of 16 inputs have been selected as variable parameters. Their variations are defined with either a range (minimum to maximum value) or discrete values as shown on Figure 3. With the Monte Carlo framework, the 16 design parameters are varied randomly 5.000 times. The resulting distribution of energy demand is shown on Figure 3 and ranges from 27.4 to 39.5 kWh/m² year. The first significant learning is that only ~2% of the calculations is within the energy frame – without considering the constraints related to daylight and thermal comfort. Figure 3 also shows the results of the sensitivity analysis, which indicate the inputs’ relative contributions to the variation in calculated energy demand. It came as a surprise to the engineers that the variation in ventilation heat recovery has more than twice the effect/influence (~8%) than the variation of specific fan power, SFP (~3.5%). This is valuable information since its easier and cheaper to install a better heat recovery than minimizing pressure loss in the entire ventilation system. Another surprise was that the variation in duct insulation was the most influential design parameter and would therefore require much attention at the design meeting. This parameter is rarely an issue since ducts are often placed in heated installation shafts but, in this case, cold ducts run from decentralized units to the façade.

The sensitivity analysis also provides insight into the influence of the detail level of the horizon angle. At this stage in the project, the same horizon angle had been used for all windows. The reason for this is that the model representation in Be18 is rather limited and as a consequence, it necessitates subjective, time-consuming approximations of the shading angles. Since window

[1] Metamodels are constructed from 3-layered feedforward neural network for which the user defines the training and test sizes and the number of neurons in the hidden layer.

positions and building rotations were still uncertain, the engineers chose to simplify the model representation and instead describe this modelling uncertainty by varying the horizon angle for all windows from 10 to 30°. The sensitivity analysis shows that this uncertainty contributes with roughly 7% to the variation in energy demand corresponding to 0.9 kWh/m². This is an approximation but it gives an idea of the possible impact of the simplification of shading objects.[2] Another thing, the horizon angle also affects thermal comfort and daylight. Ultimately, this analysis showed the engineers that the Be18 model had to be refined at a later stage and the design team should include a "buffer" for later design changes (which is common practice).

Even though main focus is on energy demand at this stage, the design team must pay attention to how design decisions may influence thermal comfort and daylight. Notably, thermal comfort may cause a challenge since the distribution of overheating hours for the corner-room (see Figure 2) ranges from 83 to 648 hours. Only 67 of the 5.000 simulations (1.3%) meet the requirement of maximum 100 hours, and this necessitates windows with a SHGC of maximum 0.37. Thus, no simulations meet both the energy frame and the thermal comfort requirement. However, actions can be taken to deal with thermal comfort in a few critical rooms without notably affecting the whole-building energy performance. For example, fixed windows may be made openable to allow for a higher air flow or the SHGC may be lowered for the "critical" rooms only. Regarding daylight, the "corrected" glass-floor-ratio ranges from 8.4 to 16.8% for the "critical" living room. Since most simulations (93%) meet the criterion, daylight seems to be of little concern. Based on these room-level results, the engineers can raise the issue with thermal comfort at the meeting and urge the design team to address it as soon as possible.

The total timeframe for this preparatory work was a roughly four hours. This includes the following: 1) selection of design parameters and definition of their variations; 2) adjusting the reference Be18 model, setting up BeDesigner, and running 5.000 simulations; and 3) interpretation of results and test of design strategies. The reported timeframe excludes the construction of the Be18 reference model, which was already set up with geometry, shading, internal loads, etc. The timeframe is similar to ordinary practice with roughly 10 to 20 manual variations which, hopefully, results in a few solutions.

MIBS framework at the design meeting

The main purpose of the meeting with the building owner and his consultants was to discuss possible solutions to achieve code compliance. The choice of design parameters and their variations was explained to all decision-makers. The distribution of calculated energy demand was presented and the few energy-compliant solutions underlined the difficulty of reaching compliance without renewables. The results from the sensitivity analysis point out that many inputs influence the energy demand. Focus should be on the most important ones, i.e. duct insulation, infiltration/air tightness, and façade insulation, while the decision-makers may somewhat ignore orientation, roof insulation, and ground insulation for the time being. With this background knowledge, the participants used the interactive coordinates plots in DataExplorer to assess the consequences of different design strategies.

By applying filters, some of the initial variations are left out, e.g. duct insulation of 100 mm for aesthetic and spacing reasons, which reduce the design space and potential solutions. Due to the large dimensionality, no solutions remain from the 5.000 Be18 simulations when adding all of the participants' requirements.[3] This issue is overcome by adding 500.000 extra design combinations using the metamodeling feature. Finally, solutions are found but it becomes clear that several costly actions are necessary to accommodate the desired constraints, e.g. 70 mm duct insulation, high airtightness, and a SHGC $\geq$ 0.47. The latter causes a challenge since, as discovered prior to the meeting, the SHGC for the corner-room has to be 0.37 or less to meet the thermal comfort criterion. Thus, other actions need to be made to ensure thermal comfort in the critical rooms. In the end, it was advised to consider renewables, which would make it easier to meet code compliance and it would provide a "buffer" for later design changes.

For this real-time design space exploration, it is worth mentioning that the construction of metamodels was done in less than a second and calculation of 500.000 new points within 10 seconds. Moreover, metamodels are rarely perfect but with R^2-values from 0.96 to 0.99 they are sufficiently accurate to reveal the correct consequences of design choices.[4]

In conclusion, the participants were positive towards this novel framework and the ability to explore (almost) all design options and find solutions in collaboration. It is doubtful that any "no renewables solutions" could be identified without it. However, if considering only a single objective (energy), a few solutions may have been found using the traditional, manual approach by choosing the most expensive options for many design parameters. But some of these may deem too costly or otherwise inappropriate that the solutions would be discarded resulting in the building owner to require more inputs, or other variations, to be considered. Then the entire preparation/simulation process would need to be repeated

[2] Assuming a linear model (R^2 of the linear regression is 0.96) and that model refinements would be within this uncertainty.

[3] Constraints: no solar cells, $U_{facade} \geq 0.15$, $U_{windows} \geq 0.9$ and heat recovery ≤ 0.87, and duct insulation $\leq$ 70mm.

[4] Inaccurate metamodels with R^2~0.4 have been shown to reveal the same trends as the true models when adjusting the constraints slightly (Østergård, Jensen and Maagaard, 2017a).

and a new meeting scheduled. Finally, the framework highlighted the necessity to consider all requirements at the same time, i.e. energy, thermal comfort, and daylight.

Subsequent design changes

A few after the design meeting, the architects shared an updated BIM-model with the engineers. Some windows had been removed, or made smaller, resulting in a reduction of window-wall-ratio from 31.5 to 26.9%. In addition, the heated floor had increased from 5.622 to 5.727 m². Such changes of BIM-models happen frequently over the course of a building design project. Unfortunately, there is not sufficient time and money to update the energy model, and other BPS models, every time. This is partly due to the lack of interoperability between Revit and the Be18 energy model. Thus, the engineers had to consider if it was necessary to spend half a day's work to redo the tedious, manual measurements. As we will show, the MIBS framework helped the engineers to make this decision.

The sensitivity analysis for energy demand shows that WWR is the fourth most influential design parameter so it does impact the energy demand significantly (see Figure 3). But what will a reduction of ~4.6% lead to? Well, that depends on other variable parameters, such as $U_{windows}$, SHGC, and Horizon (shading angle). Based on the metamodels, we can estimate this reduction of WWR while keeping the other parameters uncertain. This is done using the "what-if" table in DataExplorer, which calculates the possible outcomes of the reduction in WWR at 100 random locations in the design space (see (Østergård, Jensen and Maagaard, 2017a) for in-depth explanation). Figure 5 show that a reduction of 4.6% will reduce energy demand by 0.83 kWh/m² on average but depending on the other parameters the energy demand may reduce in the range 0.24 to 0.96 kWh/m². Based on this knowledge, the engineers could choose to postpone the update of the energy model. However, since the floor area had not been varied in the Monte Carlo simulations, we could not assess the consequences of this change using the metamodels. Though, the small increase of floor area was expected to have little, and positive, impact. The decisive argument was the aforementioned uncertainty related to the horizon (shading angle) input. Due to this uncertainty, the engineers chose to refine the inputs related to shading and update the entire energy model according to the new BIM model. Finally, we remark that the information gained from the metamodels could have been use to inform the architects about the expected consequences of changes of window-wall-ratio. Thereby, the architects would not be making changes "in the blind" but with knowledge of the most likely consequences on energy demand (and thermal comfort or daylight in the critical rooms).

	ΔX_i	$X_{i,span}$	Energy
Duct insu.		30 - 100	
Infiltration		0.7 - 1	
U,fac.		0.12 - 0.2	
WWR	-4.6	25 - 35	-0.83 (-0.96 – -0.24)
Heat rec.		0.8 - 0.9	
U,win.		0.85 - 1	

Figure 5 Screenshot of "what-if" table in DataExplorer showing the average (and min-max) response to energy demand by decreasing WWR by 4.6 percentage points.

Conclusion

In this case study, we have applied a Monte Carlo based framework which enables: 1) sensitivity analysis to inform decision-makers of important and insignificant design parameters, 2) construction of fast metamodels that enable an all-encompassing exploration of design alternatives, and 3) real-time Monte Carlo filtering and design feedback. The framework helped assist decision-making for a real building project within the same time-frame as in common practice. The following sums up valuable, project-specific insights gained from the combined framework:

- Less than 2% of 5.000 Be18 simulations met the energy frame stressing the difficulty of finding a "no-renewables" solution.
- Using metamodels to evaluate 500.000 additional combinations, it was possible to find technical solutions to the decision-makers' requirements.
- The conditions, needed to meet all requirements for the whole-building energy demand, would make it difficult to achieve thermal comfort in critical rooms for which other actions would be necessary.
- Inclusion of solar cells was advised to avoid costly solutions and to create a "buffer" for future changes and to meet with thermal comfort criteria.
- Design parameters were ranked with respect to their influence on energy demand which showed some surprises, i.e. duct insulation ranked first and the variation of ventilation heat recovery had more than twice the effect of varying the specific fan power.
- The sensitivity analysis also showed that building's rotation was of little concern.
- Sensitivity analysis revealed the shading angle, horizon, to have considerable importance calling for a refined model.
- The metamodels could be used to estimate the consequences of the reduced window-wall-ratio in the architects' updated BIM-model.

Feedback from meeting participants have been positive and they had no problems to engage with the new type of information and the interactive visualizations. They